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QUANTITATIVE COMPARISON OF FIVE SUSPENSION MODELS*

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INTRODUCTION

The selection of an entrainment model for a particular problem should be guided by the nature of the problem, and by the characteristics of the available mathematical models. Every entrainment problem has at least two facets: 1) a specific question the model is to aid in answering, and 2) the unique set of source characteristics and environmental and atmospheric conditions of the specific site. Similarly, every model is limited in several ways: 1) only a few parameters are available to represent features of the site and source, and 2) the questions a model can address appropriately are restricted by the form (units) of the estimate the model gives, and 3) the functional ability of the model to respond to changes in specific conditions may limit the situations to which it is applicable.

A specific example is used in this article to demonstrate an approach to the selection and comparison of models of particle entrainment. The problem is one suggested by Tennery et al. as being difficult to address with available techniques:¹ to estimate airborne mass flux from a hard-rock thorium ore stockpile. As a source of airborne particles an ore stockpile differs greatly from the sources used to develop an understanding of particle entrainment (sand dunes, agricultural fields, and sand or soil in wind tunnels). The hypothetical ore pile would be a mounded, angular pile consisting primarily of relatively large rocks, but including in its wide range of particle sizes the very small fines from blasting and mining. Models must be selected that are capable of reflecting the unique features of a stockpile. The major thorium ore deposit discussed by Tennery et al. is found along the continental divide near Lemhi Pass in the Beaverhead mountains of southwestern Montana. The hypothetical ore pile of this example would be located at the base of the mountains, at fairly high elevation (2200 m). This location is characterized by harsh winters with heavy mountain snowfall, and summers with frequent thunderstorms and high evaporative potential.

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erodibility) was estimated based on values for soils of similar particle size distribution. Similar approximations were made for the other parameters required.

The limited space available in this article prohibits a complete presentation of the parameter values used. This information as well as the supporting discussions and justifications for manipulating the data to provide the parameter values will be available in a report now in preparation.¹⁴

TABLE 3
AVAILABLE LEMHI PASS ORE, ENVIRONMENTAL, AND ATMOSPHERIC DATA

Ore thorium content	Monthly precipitation
Ore particle density	Monthly temperature
Ore stockpile bulk density	Winter snowpack by month
Ore stockpile dimensions	Summer evaporation by month
Ore particle size distribution	Mean wind speed
Site elevation	

TABLE 4
INPUT REQUIREMENTS OF THE SELECTED MODELS

Model	Parameters estimated from site-specific data (Table 3)	Parameters estimated from non site-specific data
Wind erosion equation	Particle size distribution Climatic factor Barrier height Ore pile width Vegetative cover	Windward knoll slope Prevailing wind direction Wind force preponderance Ridge roughness factor
Saltation driven suspension	Particle size distribution Particle density Air density Aerosol particle size	Wind measurement height Surface roughness height Wind rel. freq. distribution
UDAD/MILDOS/FGEIS	Particle size distribution Particle density Air density Mean saltating particle size	Wind measurement height Surface roughness height Wind rel. freq. distribution Ore pile moisture content
Combined Suspension	Particle size distribution Particle density Air density Vegetative cover	Wind measurement height Ridge roughness factor Wind rel. freq. distribution Ore pile moisture content 15-bar moisture content No./size of roughness elements Threshold friction velocity Atmospheric stability class
Parametric emission rate	Source surface area Mean wind speed Ore pile bulk density Precip.-evap. index	Empirical emission constant

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Although these parameter values are not entirely defensible they are consistent from model to model, and they permit us to proceed with the comparison of models. We feel this is an important point. Lack of data is a serious problem, but it should not be used as an excuse for the selection of an inappropriate model. By continuing the comparison using artificial data it is at least possible to determine whether or not a model is inherently unsuitable for the problem. Also, it may be possible to estimate the sources and magnitude of potential error through sensitivity and error analyses.

COMPARISON OF MODEL RESPONSES

Results of running each model with parameter values estimated for Lemhi Pass are given in Table 5. Three of the four models give estimates in comparable ranges. The parametric emission rate is not capable of producing an estimate in the absence of a measured emission rate. No judgment of the models can be based on these estimates, partly because there is not sufficient information to evaluate the way the model is responding to the particular features of the ore pile or conditions of the site, and partly due to the lack of validation data.

TABLE 5
ESTIMATES OF MASS FLUX FROM A THORIUM ORE STOCKPILE

Model	Mass Flux (g/m ² -yr)		
	Saltation > 80 μ m	Suspension < 20 μ m	Respirable < 7 μ m
Wind erosion equation	110	*	*
Saltation driven suspension	250000	*	170
UDAD/MILDOS/FGEIS	210	1.0	0.7
Combined suspension	100	0.8	0.5
Parametric emission rate	*	*	*

* No independent estimate possible.

Of the models in Table 5, only the wind erosion equation has received significant validation (comparison of predictions to field measurements). That two other models give comparable saltation estimates is encouraging, but not necessarily significant. Validation of the wind erosion equation was accomplished on agricultural fields; there is no guarantee that it can produce reliable predictions for a source as unique as an ore stockpile.

Sensitivity Analysis.

The response of model estimates to changes in the input parameters provides information that allows model performance to be compared for the conditions

representative of an ore stockpile. For some parameters, values representing an ore pile may be outside the realm for which the models were developed. It should not be surprising if unusual or meaningless model responses are found. One sin of modeling is the application of models to problems outside their intended range of use, and this analysis aids in evaluating that condition.

Two approaches were used. First, each parameter was varied over a range representative of Lemhi Pass conditions, while all other parameters were held at a baseline value. The results are described below in terms of parameters with minor influence (effect on estimate less than a factor of two), and those with higher influence (effect on estimate greater than a factor of two). Second, a maximum range estimate was produced using complementary extremes of all parameters. This is not a realistic method for producing an uncertainty value for a model's output. The calculation of an uncertainty value is more reasonably based on statistical sampling of the parameter distributions¹⁵ and is an area in which more effort is needed.

Wind Erosion Equation. As parameter values were varied in the analysis of this model it quickly became apparent that a single result was returned regardless of the input, with the exception of one influential input parameter. The interpretation of this problem, based on Figure 1, is that the wind erosion equation is not intended to be used for particle size distributions as heavily biased toward large particles as an ore pile. The non-erodible pile mass is estimated to exceed 88 % for the mined ore. In this range, erosion estimates show no response to particle size or any other input parameter except the model's climatic factor. This combined measure of wind speed and average soil moisture produced an erosion response only for values indicative of erosive conditions considerably greater than that likely at Lemhi Pass. Its effect is to raise the curve of Fig. 1 along the ordinate, with only a minor effect on the curve's shape.

It seems, then, that an ore pile is at the limit of applicability of the wind erosion equation. The best interpretation of its estimates is as an upper limit for ore pile particulate release since a realistic response would have the curve of Fig. 1 continuing to drop for non-erodible masses exceeding 70 %. The total range of variability due to the climatic factor is 110 to 400 g/m²-yr (net mass loss).

Saltation Driven Suspension. In the sensitivity analysis of this model several anomalies were observed, such as in Fig. 2 where the saltation rate decreases at one point as the wind speed increases. This and other physically

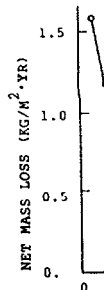


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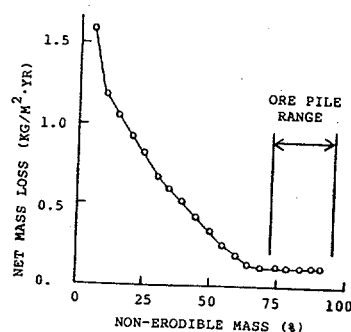


Fig. 1. Wind erosion equation: soil loss response to percent non-erodible (> 840 μm) soil mass.

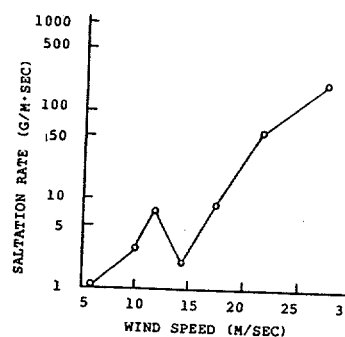


Fig. 2. Saltation driven suspension: discontinuous saltation response to wind speed.

unrealistic responses were traced to a problem with the algorithm used to apportion the mass of different particle size classes to the saltation flux as a function of wind speed. The problem might be due to the thorium ore pile particle size distribution, which is highly enriched in the larger sizes. It is not clear if the model contains a faulty algorithm or if it is merely pressed beyond its applicable range.

UDAD/MILDOS/FGEIS. This model appears to function as it was intended as its input parameters are varied over ranges representative of an ore pile. Several parameters were found to have only minor influence: air density, ore density, and wind measurement height. Parameters of higher sensitivity were soil moisture content, surface roughness height, wind speed relative frequency distribution, and those describing the particle size distribution. Responses to surface roughness height and soil moisture content are shown in Figs. 3 and 4. The total range of suspension estimates obtained using complementary extremes for all parameters is 0.01 to 128 $\text{g/m}^2\text{-yr}$ (< 20 μm particle diameter), with a comparably large range for saltation and respirable sizes. Errors in parameter values are not likely to be biased all towards one extreme, however, and considerably less error-induced variability is a realistic expectation.

Combined Suspension. This model, as for the previous one, seemed to function as intended for parameter values representative of an ore pile. The parameters having minor influence were the same: ore density and wind measurement height. The parameters having moderate to high influence were those describing soil moisture, particle size distribution, ridge roughness, and wind speed relative frequency distribution. While all responses were in general agreement with physical expectations, the ridge roughness and soil

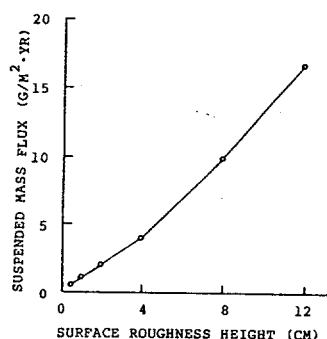


Fig. 3. UDAD/MILDOS/FGEIS: response of mass flux to a measure of surface roughness.

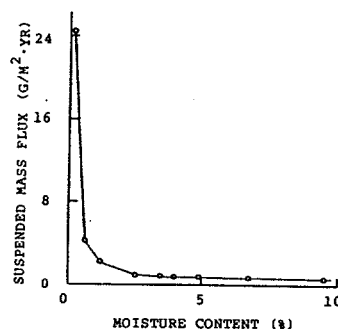


Fig. 4. UDAD/MILDOS/FGEIS: response of mass flux to ore moisture content.

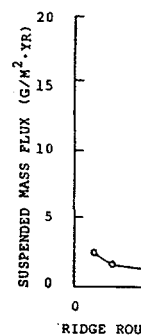


Fig. 5. Combined response of mass flux to a measure of surface roughness and moisture content.

moisture parameters generated responses (Figs. 5 and 6) different from those of comparable parameters in UDAD/MILDOS/FGEIS. The total range of variability induced by complementary extremes is 0.04 to 10.3 g/m²-yr (< 20 µm particle diameter), with a comparable range for the saltation and respirable sizes.

Parametric Emission Rate. To provide the emission constant required to allow sensitivity analysis with this model, we chose the average of the suspended fluxes given by the UDAD/MILDOS/FGEIS and combined suspension models (0.9 g/m²-yr). None of the parameters for the parametric emission rate exerts as strong an influence on this particulate release estimate as they do in the more mechanistic models. This is reflected in the small total range of variability, 0.3 to 1.2 g/m²-yr (< 20 µm particle diameter), and is due in part to the annual averaged nature of all of the input parameters.

CONCLUSIONS

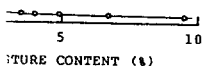
The wind erosion equation and the saltation driven suspension models were found to be not suitable for the thorium ore stockpile problem due to the problems noted above. The parametric emission rate model is also unsuited to a hypothetical problem where measurements of particle suspension cannot be made to provide the site-specific emission constant.

The combined suspension and UDAD/MILDOS/FGEIS models were found to be the most suitable, although neither fully describes all features of an ore pile. Also, neither has been subjected to validation for any type of source, a considerable failing. Both require parameters for which it is difficult to provide reasonable values: soil moisture content and surface roughness height

for UDAD/MILDOS/FGEIS. The velocity for saltation and suspension are similar parameters, and other might be considered. Differences in the

Benefits of the suspension model, information, values. Our results are about 1 g/m²-yr, influences of the model observed for the sources for the model emphasize the reasonable average

The results of the extreme characteristics of the sandy material, wind erosion, nature of the source, in the saltation, common source, constant could



MILDOS/FGEIS: response to ore moisture content.

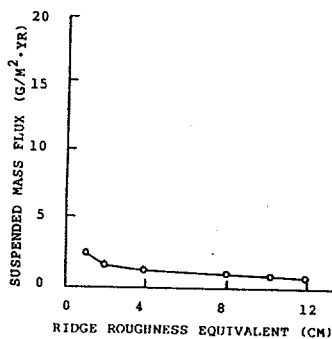


Fig. 5. Combined suspension: response of mass flux to a measure of surface roughness.

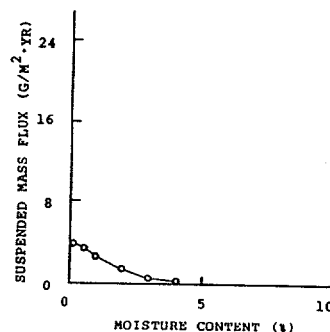


Fig. 6. Combined suspension: response of mass flux to ore moisture content.

for UDAD/MILDOS/FGEIS, and soil moisture content and threshold friction velocity for combined suspension. Some differences in their response to similar parameters were noted, and a final selection of one model over the other might require a consideration of the sources and the importance of those differences.

Benefits of these models include the ability to calculate particle suspension from data of known quality, to tailor the estimate with seasonal information, and to estimate the error resulting from uncertainty in parameter values. Our best estimate of the mass flux ($< 20 \mu\text{m}$ particle diameter) is about $1 \text{ g/m}^2\text{-yr}$, with a maximum range due to parameter error or environmental influences of less than 0.01 to $100 \text{ g/m}^2\text{-yr}$. This range is comparable to that observed for resuspension factor values. It indicates there are identifiable sources for the variability observed in resuspension factors, and serves to emphasize that such factors must be based on long-term measurements if a reasonable average value for a site is desired.

The results of this comparison might be changed if a source having less extreme characteristics were used. For a uranium mill tailings pile (a fine sandy material), for example, a reasonable particle size distribution for the wind erosion equation would have been available. The less strongly skewed nature of the particle size distribution might have allowed the algorithm used in the saltation driven suspension model to work properly. For a relatively common source like a mill tailings pile it is possible that a generic emission constant could be developed for the parametric emission rate model. This would

different from those of range of variability $< 20 \mu\text{m}$ particle and respirable sizes. constant required to the average of the combined suspension models. emission rate exerts estimate as they do in the total range of (ster), and is due in part eter

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add a simple yet reasonably parametric model to the available battery of techniques. These models should certainly be reevaluated for such an application.

The combined suspension and UDAD/MILDOS/FGEIS formulations may seem too highly parametric for an application such as a smooth, sandy mill tailings area. But then, they may have the necessary functional dependencies to allow consideration of specific problems not addressable by the others.

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